Analytic models of the spectral properties of gravitational waves from neutron star merger remnants

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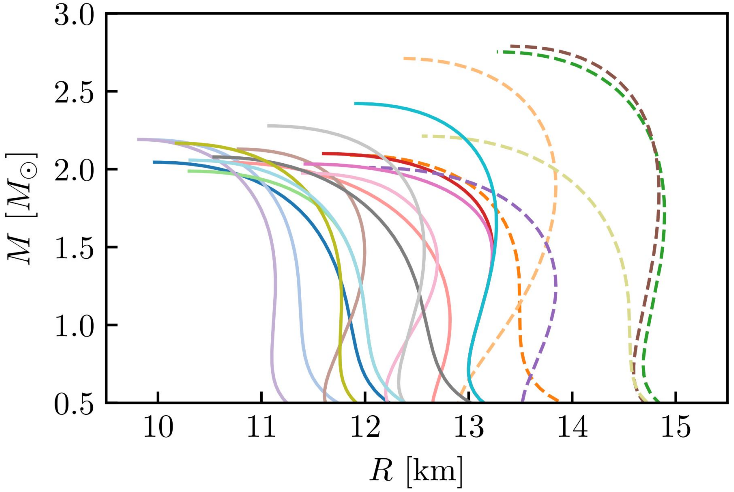
HITS

Equation of state

- The equation of state (EoS) of a neutron star is incompletely known but theoretical models can be computed (with some uncertainties)

Neutron star mergers and post-merger phase → High density regime



Adapted from Lioutas et al. (2021)

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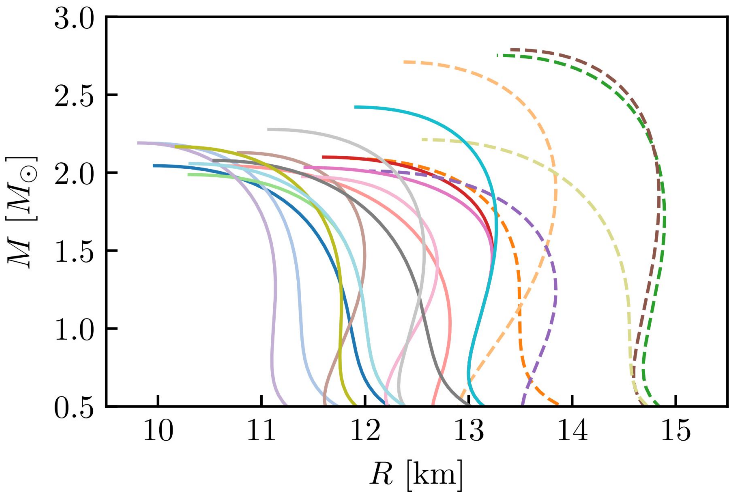

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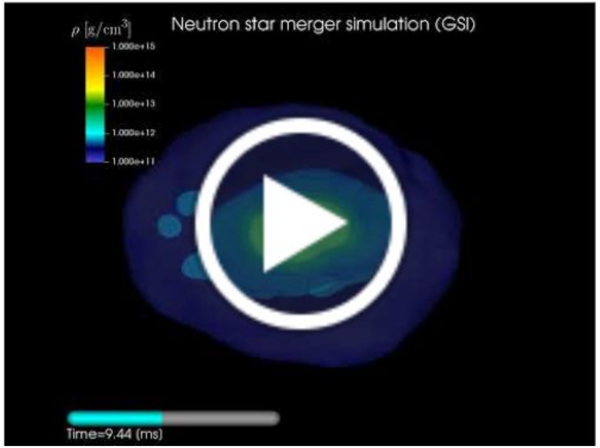


Credit: S. Blacker

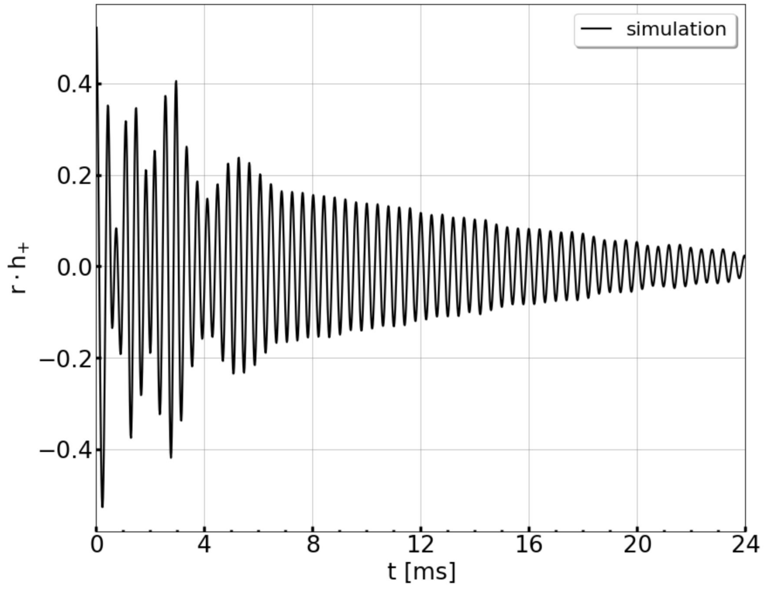
Motivation

- To detect gravitational waves (GWs) we need to know how GWs look like

Solutions for GWs from neutron star merger remnants ⇒ Matched-filtered search on LVC measurements

- Analysis for potential candidates is long and computationally expensive

Fast and accurate analytic models



Simulation setup

- Simulations of binary neutron star mergers using the Einstein Toolkit (full GR and grid-based hydrodynamics)

- Sequence of models with increasing total mass using the MPA1 EOS (compatible with current constraints)

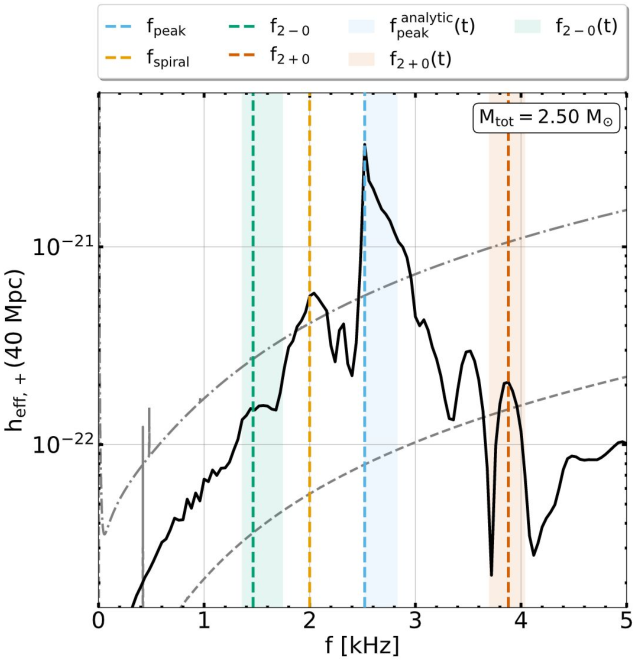
- total masses of $M_{\rm tot}$ = [2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3.0, 3.1] $M_\odot$ and ratio q=1

  reference model: $M_{\rm tot} = 2.5\ M_\odot$

- Numerics:
  - spacetime evolution with Z4c formalism
  - WENO reconstruction, HLLE Riemann solver
  - dx = 0.1875 GU = 277 m, x_{max} = 1440 GU = 2126.28 km

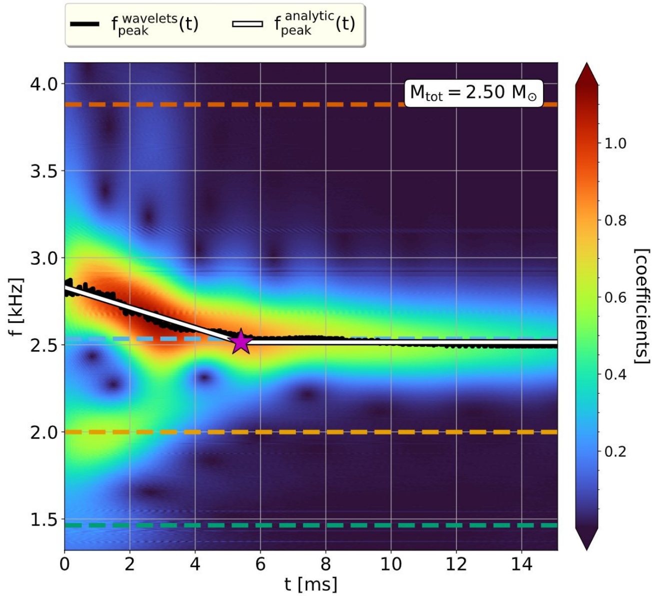
Spectral analysis

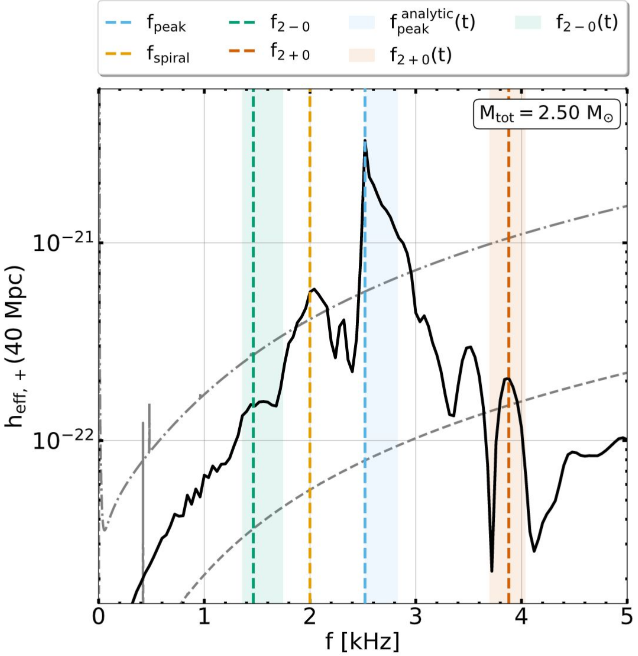
Evolution of f_{peak}



Evolution of f_{peak}

- We use spectrograms and parametrize the instantaneous f_{peak}
- 3-parameters: $\zeta_{\mathrm{drift}}, t_*, f_{\mathrm{peak},0}$

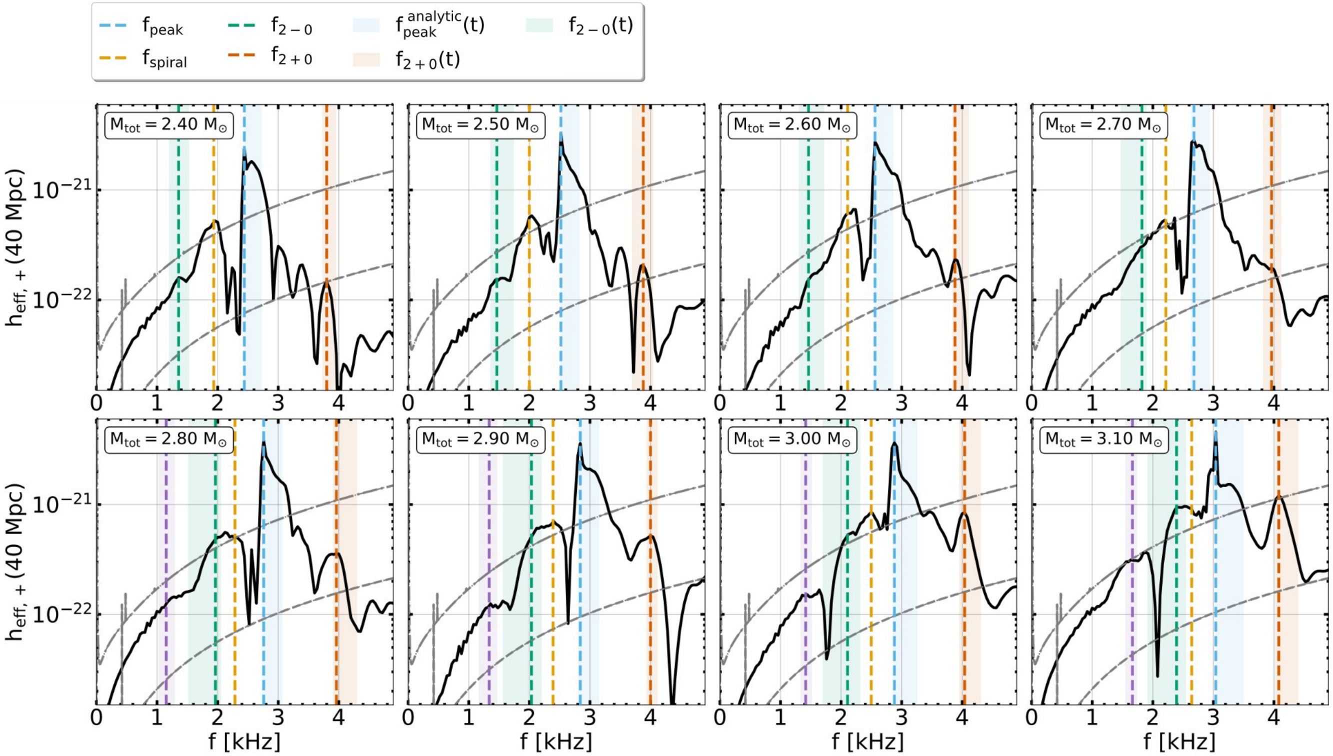




$$f_{\mathrm{peak}}(t) = \begin{cases} \zeta_{\mathrm{drift}} \cdot t + f_{\mathrm{peak},0} & \text{for } t \leq t_* \\ f_{\mathrm{peak}}(t_*) & \text{for } t > t_* \end{cases}$$

Sequence of models of increasing total binary mass

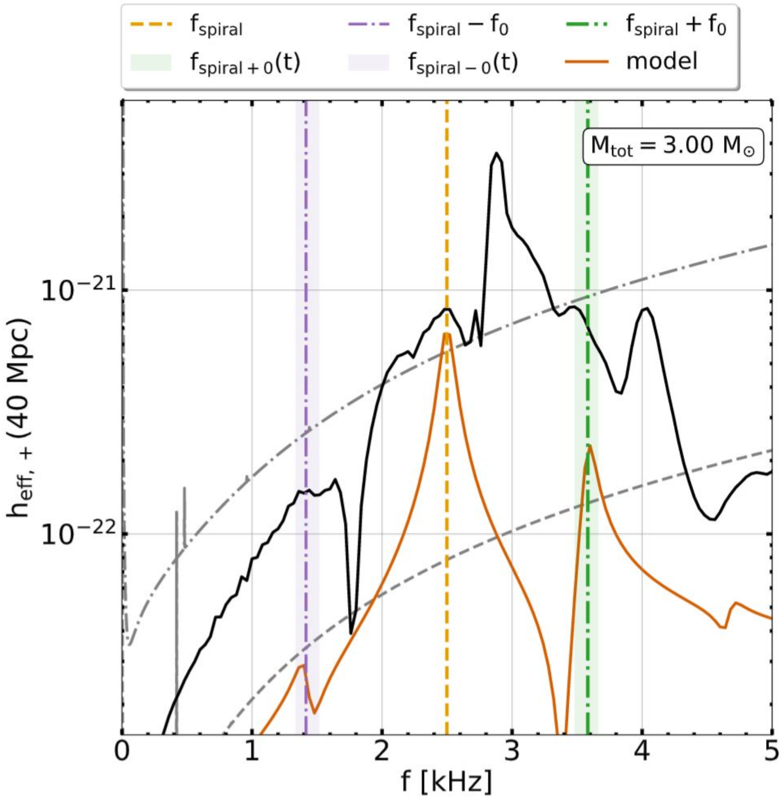
- Evolution of the spectral features depending on total binary mass



New coupling mechanism

- coupling between the ***tidal bulges*** and the ***radial*** oscillation mode

$$f_{\mathrm{spiral}\pm 0} = f_{\mathrm{spiral}} \pm f_0$$



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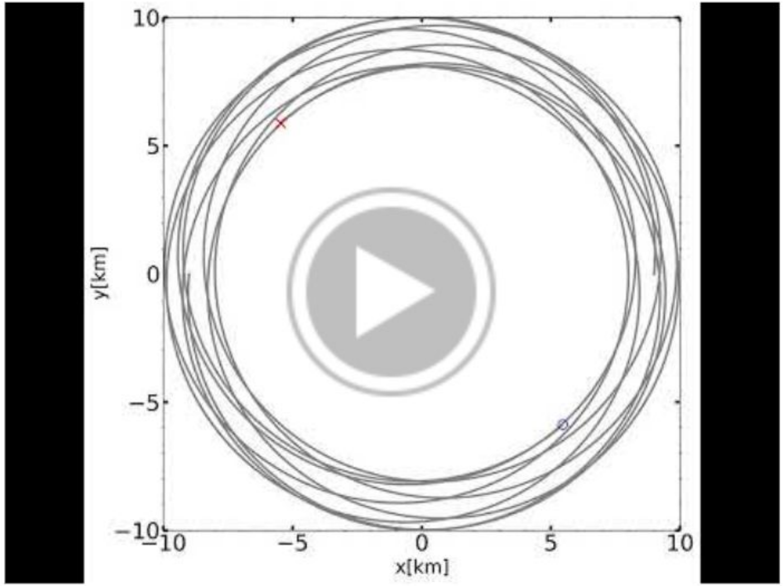
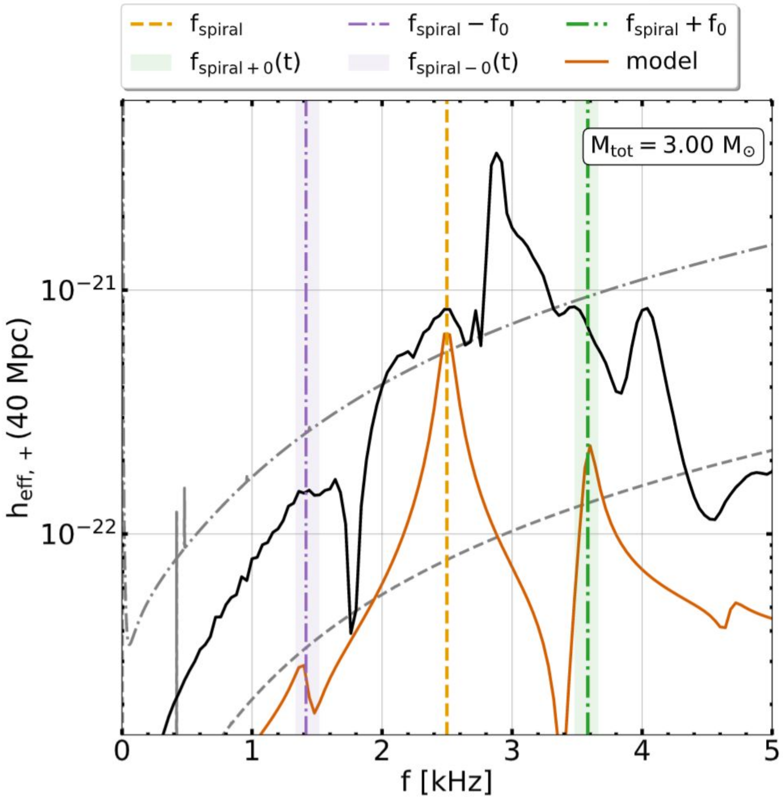
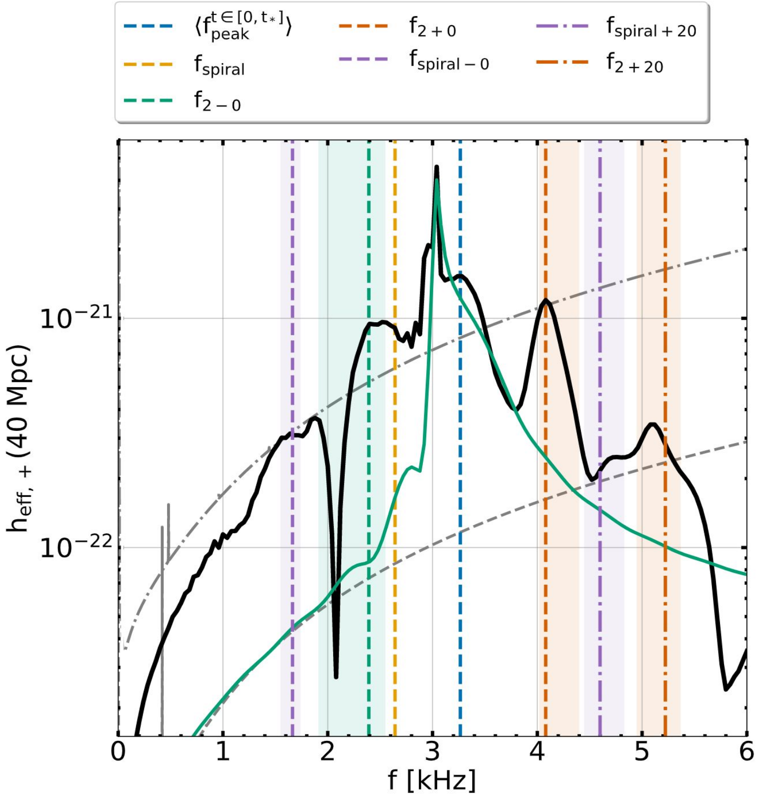




Models close to prompt collapse

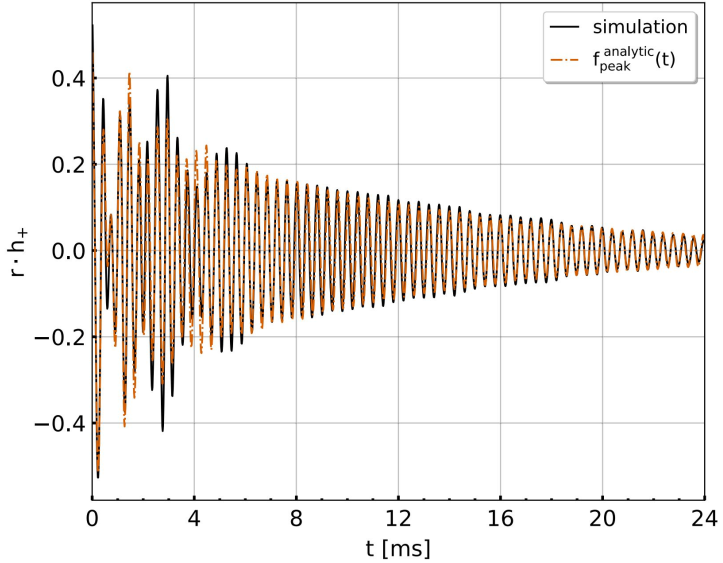
- Different components and their couplings explain most features up to 6 kHz



Analytic model

Analytic model: reference model

- Exponentially decaying sinusoids
  - time-dependent f_{peak}
  - 3 secondary components: $f_{\mathrm{spiral}}, f_{2\pm0}$



$$
\begin{aligned}
h_+(t) = {} & A_{\mathrm{peak}}\ e^{(-t/\tau_{\mathrm{peak}})} \cdot \sin(\phi_{\mathrm{peak}}(t)) \\
& + A_{\mathrm{spiral}}\ e^{(-t/\tau_{\mathrm{spiral}})} \cdot \sin(2\pi f_{\mathrm{spiral}} \cdot t + \phi_{\mathrm{spiral}}) \\
& + A_{2-0}\ e^{(-t/\tau_{2-0})} \cdot \sin(2\pi f_{2-0} \cdot t + \phi_{2-0}) \\
& + A_{2+0}\ e^{(-t/\tau_{2+0})} \cdot \sin(2\pi f_{2+0} \cdot t + \phi_{2+0})
\end{aligned}
$$

where

$$
\phi_{\mathrm{peak}}(t) = \begin{cases} 2\pi \left(f_{\mathrm{peak},0} + \frac{\zeta_{\mathrm{drift}}}{2} t \right) t + \phi_{\mathrm{peak}} & \text{for } t \le t_* \\ 2\pi f_{\mathrm{peak}}(t_*) \left(t - t_* \right) + \phi_{\mathrm{peak}}(t_*) & \text{for } t > t_* \end{cases}
$$

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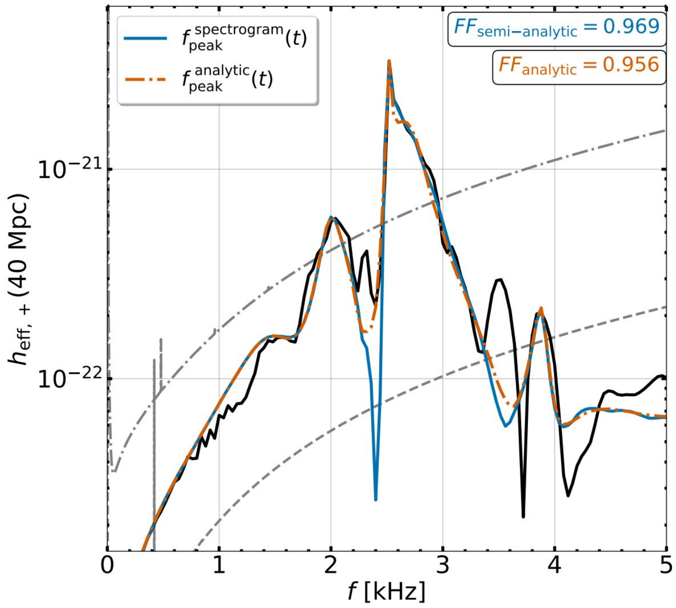
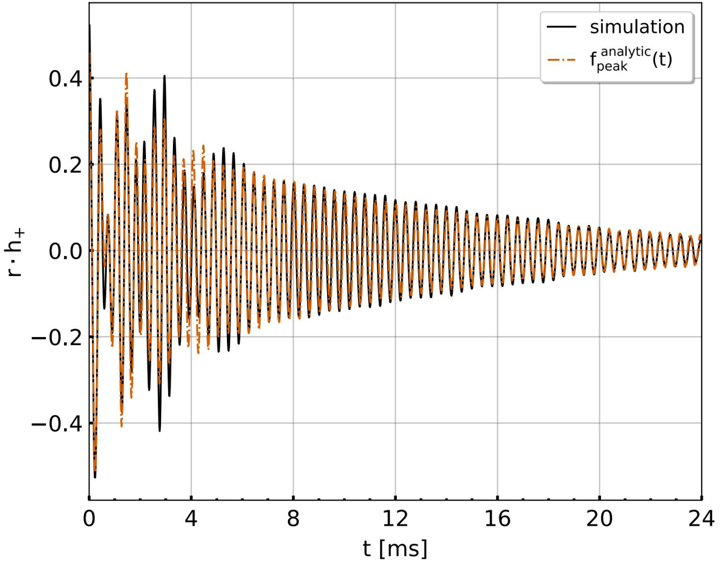
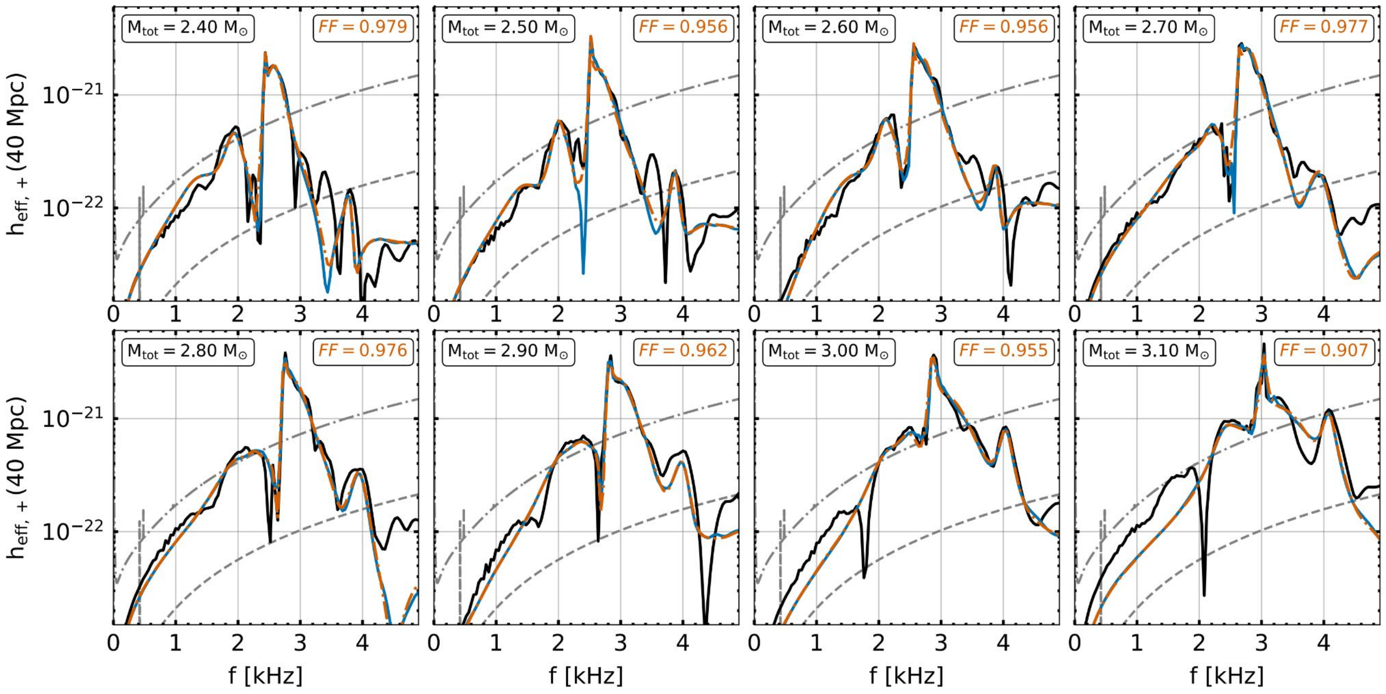




Analytic model: mass sequence

- The analytic model reproduces well the f_{peak} peak for the mass sequence models

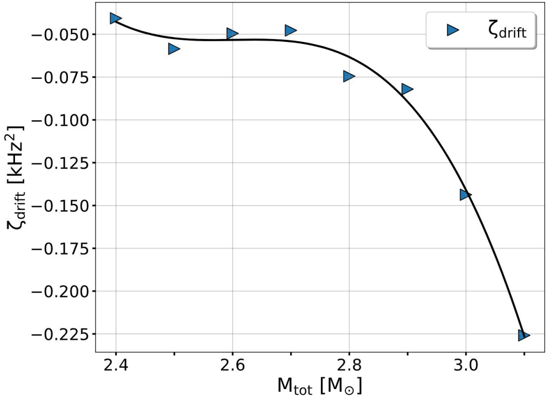
- FFs >0.95 for the majority of models



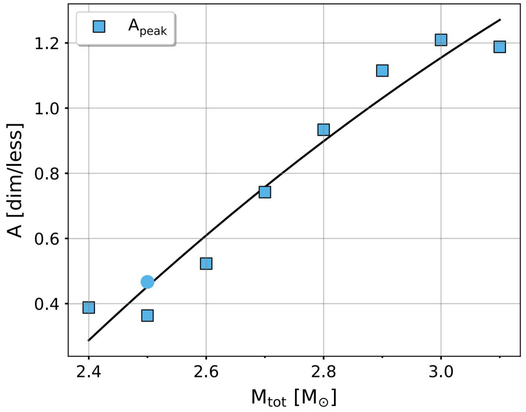
Correlations between model's parameters

- Specific trends for the description of $f_{\text{peak}}(t)$

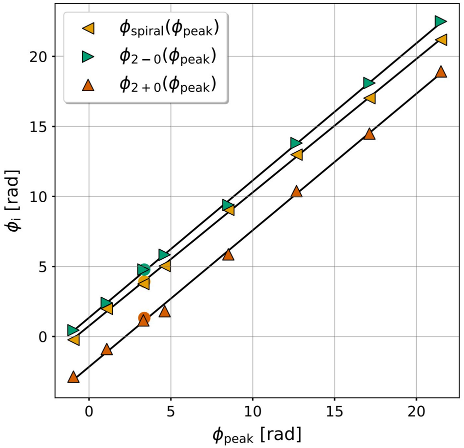
$$f_{\text{peak}}(t) = \begin{cases} \zeta_{\text{drift}} \cdot t + f_{\text{peak},0} & \text{for } t \leq t_* \\ f_{\text{peak}}(t_*) & \text{for } t > t_* \end{cases}$$



- Dominant mode dependence of total mass



- Tight dependence of ϕ_{spiral}, $\phi_{2\pm0}$ on ϕ_{peak}
  - slope close to 1



All parameters correlate (within some uncertainty) with total binary mass M_{tot}

Summary

- Smooth transition of the spectral features depending on the total mass

- New coupling between the *antipodal bulges* and the *quasi-radial mode*: $f_{\mathrm{spiral}\pm 0}$

- Analytic models with *exponentially damped sinusoids* performs well (FFs > 0.95)
  - 2-segment analytic linear description of $f_{\mathrm{peak}}(t)$

- All parameters of the analytic model correlate with the total binary mass M_{tot}

Link: